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Predicting the Service Lives of Materials of Construction

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Abstract

Reliable predictions of the service lives of new construction materials (and components), or of any construction material or system in a new application, are a continuing need. However, though predictions are essential, present-day service life predictions may merely be unreliable deductions from imperfect knowledge, not based on sound materials science. Among major factors contributing to uncertainties in service life predictions are lack of knowledge about: service conditions, defects and flaws in materials, degradation mechanisms and the kinetics of degradation under likely service conditions, and the appropriate failure criteria; also, in the present state of knowledge, another important factor is the variability in the knowledge and insights of persons responsible for making the predictions. To prepare for a new generation of safe and durable constructed facilities, several actions should be taken. These include: facilitate use of a standard methodology for prediction of service life and provide subsidiary standards to aid application of the parts of the methodology (such as, for example, how to characterize service environments); develop the databases and integrated knowledge systems needed to support service life predictions; and develop guidelines expressing recommended qualifications for those entrusted with the responsibility of predicting service lives of construction materials. Some of these developments are already taking place, but they should be expedited.

Introduction

Reliable predictions of performance, particularly service life, of construction materials, components and systems will be essential in the creation of a new generation of safe and durable constructed facilities consistent with the recently-established National Construction Goals [Wright, Rosenfeld & Fowell]. If designers are to have confidence in predictions of service life of materials as they strive to meet the goal of "50 percent increase in durability and flexibility", a substantial change will be required from the way

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material which are important to the user are sustained over time under the expected service conditions. While it is becoming possible, though still difficult, to predict many properties of materials from knowledge of their composition and microstructure [NMAB, 1988], predicting the service lives is much more difficult because of the need to predict the service environments and rates of degradation as well. Nevertheless, there is growing awareness that improved ways of predicting the performance of construction materials over time is needed and that useful predictions of service life and other aspects of performance should be possible [e.g., Jennings, Kropp & Scrivener; also Frohnsdorff, Clifton, Garboczi & Bentz]. Prediction of service life is challenging because it implies ability to predict all critical aspects of performance. Service life prediction is a problem faced whenever a new material without a significant performance history is proposed for use; inability to make reliable predictions can be a major barrier to acceptance of new materials. The problem exists for all construction materials but tends to be greatest for composite materials -- such as concrete, pigmented coatings, and fiber-reinforced polymers -- which are formed by the blending and processing of mixtures of materials some of which maintain their properties in the composite product.

The making of the most rational service life predictions requires knowledge of *materials science,* the study of relationships among the composition, processing, microstructure and properties of materials; *materials engineering,* the related subject concerned with the application of material science to the manufacture or selection of materials to meet specific performance requirements; and *reliability theory,* a predictive tool that uses knowledge gained from materials science and materials engineering, together with life data, in estimating service lives of materials, components and systems [O'Connor]. The essence of materials engineering is selecting materials that will perform as required in a given application [Ashby; Budinski]; ideally, it is selecting the material that will give the optimum performance in the application, with life-cycle cost being one of the most important attributes to be considered. In any case, the need is to make the most effective and appropriate use of available data, knowledge, and resources.

Need for an Accepted Standard Methodology for Service Life Prediction

The major civil engineering materials are metals such as steel and aluminum; non-metallic inorganic materials such as concrete, soil, brick, and glass; and predominantly-organic materials such as paints and coatings, wood, asphalt, and plastics, with polymer matrix composites being of growing interest. Predicting the service life of any of these materials in a generalized service environment is difficult, but of great practical importance. As will be discussed later, the problem and the need can be put in perspective by asking how to determine whether a building or other facility of a particular design will achieve its design life.

The need for a standard methodology for predicting service life of construction materials was made apparent to the author in the early 1970s with the need to evaluate, on a common basis, the "durability" of many different types of adhesively-bonded structural sandwich panels proposed for use in Operation Breakthrough [Leyendecker].

current predictions are made. The predictions are usually imperfect -- they are seldom based on inference from a sound knowledge of materials science or performance data from a significant population of closely-related materials exposed to similar service conditions. (For conciseness in what follows, the word "materials" should usually be taken to mean "materials, components and systems.") How to help improve predictions of service life, the most demanding aspect of performance, is the theme of this paper. It is a theme that is highly relevant to the development of the "sustainable engineering" that will become increasingly important in the 21st Century [Bernstein & Lemer]. It is relevant to point out that the subject is common to many branches of technology and that there is much to be learned from others. For example, the first words in the preface to a recent National Materials Advisory Board report [NMAB, 1996] concerned with materials for future high-speed civil air transports might just as well have been written for the present paper:

> A fundamental understanding of the physical phenomena associated with damage and failure must be developed to predict the response of a materials system to long-term exposure in a service environment. This can only be established by experimental materials characterization and development of the associated mathematical and computational models that describe the physical phenomena. While test methods and modeling codes are available to provide guidance on specific types of component design and test methodologies, these methods and models may require refinement and standardization.

For the purpose of the present paper, it must be recognized that "prediction" can be interpreted in several ways. While "to predict is usually to foretell with precision of calculation, knowledge, or shrewd inference from facts or experience .....; it may, however, be used quite lightly" [Webster]. For innovative materials and systems, predictions which "foretell with precision of calculation" are vital but, in the present state of knowledge, many predictions are based on inference, not necessarily "shrewd", from imperfect knowledge. With this as background, a "service life prediction" may merely imply a conclusion, however arrived at, about how a material or component will perform over time in its expected service environment. Those who recommend or select a material or component for a given application are, in effect, making a prediction, whether explicit or implicit, that the material is suitable and will perform satisfactorily for its intended life. Since the service environment itself must be predicted and, for a construction material, the service environment will often be weather-dependent, uncertainties in the weather are likely to cause uncertainties in service life predictions. Other causes of uncertainty will be discussed later. Our goal should be to understand the uncertainties and to be able to quantify and minimize them to the extent that it is practical and economical to do so.

For a construction material, "performance" is often considered to be a difficult concept to deal with because it is not well-defined like a property of a material, but it is a description of many aspects of its behavior over time in service. One internationally-accepted definition of performance is: "behavior (of a product) related to use" [ISO]. Performance of a material might also be described as the degree to which properties of a

The panels differed widely in the compositions of their skins and cores, and in the adhesives used to bond skin and core together. This need led to the establishment of a subcommittee on "Durability Performance of Building Constructions" in ASTM Committee E06, Performance of Buildings. The purpose of the subcommittee was to provide a standard methodology for service life prediction. As its first product, the subcommittee drafted ASTM E-632, Standard Practice for Developing Accelerated Tests to Aid Prediction of Service Life of Building Components and Materials [ASTM]. ASTM E-632 then stimulated development of a closely-related international document, the RILEM Technical Recommendation, Systematic Methodology for Service Life Prediction of Building Materials and Components, which was published by RILEM (the International Union for Research and Testing Laboratories for Materials and Structures) in 1989 [Masters & Brandt].

Essentially, ASTM E-632 and the RILEM document provide generic guidance on steps to be taken in developing accelerated tests for use in obtaining information needed in service life prediction. The key steps are:

- Define the failure criteria of the material relevant to the application
- Characterize the service environment
- Characterize the material on a level relevant to the likely degradation mechanisms
- Identify degradation mechanisms of the material by exposing specimens to very severe conditions to identify failure mechanisms as quickly as possible
- Deduce, or otherwise decide, which types of failure are likely to occur under the normal range of conditions
- Determine the kinetics of degradation of the material in the expected service environment
- From the kinetics of degradation and the failure criteria, calculate the time to failure in the expected service environment
- Report the results and include an explicit statement of the assumptions made.

Although the methodology is logical and easy to understand, it is difficult to apply because its use requires much judgment. However, it should become progressively easier to apply as sound test protocols are established and good data on environments, degradation mechanisms, and degradation kinetics become available for reference. In spite of the difficulties, the potential benefits of having rational, standardized methods for producing service life predictions of known reliability for use, for example, in life cycle costing and life cycle assessment of new generation facilities, justify a sustained effort to bring such methods into widespread use.

The main variables determining the service life of a typical material are: i) the service conditions, ii) the material, iii) the geometry and orientation of the element of the material under consideration, and iv) the failure criteria. If a service life prediction is not made in a standardized manner, the result may be much affected by the judgment of the person in charge (who will here be referred to as the decision-maker).

Recognizing the stochastic nature of the variables in service life prediction, a probabilistic (or reliabilistic) approach is needed if the uncertainties in predictions are to be properly assessed [O'Connor]. Applications of the reliability approach to determination of service lives of construction materials have been described by several authors [Siemes; Sarja & Vesikari; Martin, Saunders, Floyd & Wineburg]. While Siemes, and Sarja and Vesikari, focus primarily on concrete, Martin et al. focus on organic coatings. Nevertheless, the principles are the same and, as Siemes points out, the reliability approach is consistent with the methodology of the previously-mentioned RILEM Recommendation [Masters & Brandt], and the approach is equally applicable to degradation by any agent, whether mechanical, physical, chemical or biological. The approach is analogous to that for performance-based structural design, except that where the resistance, R, and the load, S, are normally represented as time-independent quantities in structural design, for performance-based service life (durability) design they have to be rewritten as functions of time, R(t) and S(t). Unfortunately, until those concerned with construction materials recognize the benefits of the probabilistic approach, collect the appropriate data, and build the needed databases, the technique will not be able to be applied without great effort. Also, until the need for probabilistic service life predictions is more generally recognized and the technique is more widely adopted, much will depend on the judgment of the individual decision-maker. To the extent that assumptions made in making a prediction are not precisely correct, an error of uncertain magnitude will occur in the predicted service life. It is therefore critical that appropriate predictive functions and appropriate values of the variables be selected if the performance prediction is to be as reliable as possible. This should be a responsibility of the decision-maker.

The Human Factor In Service Life Prediction

The importance of the human factor in determining the reliability of service life predictions should be apparent from the previous section. However, in spite of its importance, it is seldom addressed explicitly. Rather, the selection of materials is left to the judgment of persons in the design and construction team who may not be the best judges of the reliability of service life predictions of non-traditional materials, or any material to be used under unusually demanding conditions. As a result, material selection may be unnecessarily conservative, or offer an unnecessarily high risk of failure. Some well-documented, relatively recent examples of costly failures from several different countries due to unexpectedly rapid deterioration of non-traditional materials in traditional applications are:

- Deterioration of some flame-retardant-treated plywood

- Corrosion of steel wall ties by mortar formulations containing a chlorine-containing vinyl polymer latex
- Cracking of polybutylene water pipe
- Distress of steam-cured concrete railroad ties due to a mechanism which has been referred to as delayed ettringite formation
- Corrosion of reinforcing steel in steam-cured precast concrete elements
- Loss of strength of concrete beams made with calcium aluminate cement
- Embrittlement and fracture of some PVC roofing membranes.

While it is not possible to be sure that a completely foolproof and practical system for avoiding all failures such as these could be developed, it seems to the present author that most of these types of failures should have been foreseeable by a material scientist or materials engineer trained in service life prediction and following a test methodology such as that described in ASTM E-632. This might suggest that service life prediction should be recognized as a specialty by the design profession and building code authorities. A current example of a class of materials where reliable predictions of service life are critically needed is the fiber-reinforced polymer-matrix composites proposed for structural civil engineering applications.

<u>From Prediction of Service Life of Construction Materials to Design life of Facilities</u>

If it is difficult to predict the service life of a single material of simple geometric shape in a single set of conditions, it is more difficult, though a conceptually similar problem, to predict the service lives of all the different materials that go into a building or other facility and which are subjected to different mechanical loads and service conditions. This is a problem being addressed by the working group, ISO TC59/SC3/WG9, Design Life of Buildings, in the International Organization for Standardization; the working group is developing a standard to ensure that, with planned maintenance, the design life of a building will be met. The approach [Browne & Soronis] is to divide the problem into four main parts each of which should evolve over time and become progressively easier to use. The topics to be addressed in the parts are:

1. data in standard formats for individual materials and components. Design for service life -- rules for designing for service life of buildings from scratch
2. Prediction of performance (service life) of individual materials and components
3. Auditing the finished design and maintenance plan for consistency with the design life
4. Generation and computerization of reference service life

The working group will also develop at least one ancilliary standard recommending the types of data for use in service life predictions that should be made available by material manufacturers and suppliers.

Service Life Prediction for Some Specific Construction Materials

The performance of metals, particularly steel, and factors determining their rates of corrosion, have been studied intensively. As a result, the literature on the corrosion of metals provides the best and most systematic information for making predictions (estimates) of service life of construction materials. The situation with non-metallic materials is less satisfactory. To help improve the situation, the series of triennial International Conferences on the Durability of Building Materials and Components was started in 1978 [Sereda & Litvan]. The objective was to provide a forum for discussion of matters relating to the prediction of service life of non-metallic materials complementary to that on corrosion of metals and to publish conference proceedings that would help fill the information gap. The conferences are making an important contribution, but they cannot provide all the knowledge that is needed. This section is concerned with service life prediction where failure due to chemical degradation is, at least potentially, the main determinant of service life. The proceedings of the 1996 conference provide a valuable entry to the literature on durability and rational service life prediction [Sjostrom].

Environmental characterization -- A key step in predicting service life of a material is obtaining an adequate description of the service environment. For this reason, environmental characterization will be discussed before discussion of prediction of the service life of specific classes of materials. Environmental characterization This is not a trivial matter. For example, if reliable predictions are to be sought for materials to be exposed to natural environments, it should not be arbitrarily assumed that it will not be sufficient to describe the environment only in terms of relatively-easily obtained data such as mean summer and winter temperatures and mean seasonal rainfall [Saunders, Jensen, and Martin]. A recent addition to the literature addresses environmental characterization in the context of development of dose-response functions and their application in service life prediction [Haagenrud & Henriksen]. In summarizing some dose-response functions developed for various materials, mostly metals, the report illustrates the lack of consistency among researchers in their selection of environmental variables to be measured. Haagenrud and Henriksen discuss environmental agents that should be considered, how they may be measured, and how the data may be used in air quality models and maps.

Metals -- Techniques for determining the rates of corrosion of metals, whether general or localized corrosion, are well-documented [e.g., Jones] and there is also much corrosion rate data in the literature [e.g., Schweitzer]. As with service life prediction in general, informed judgment is required in deciding which, if any, of the published data is relevant and it must always be borne in mind that the predictions will have an uncertainty the magnitude of which should be estimated as well as possible [O'Connor]. The paper by Haagenrud and Henriksen references several examples from the recent literature with an emphasis on dose-response functions for metals in polluted atmospheric environments. In any case, it must be recognized that, as for metals in actual structures, the results may depend markedly on the composition and microstructure of the metal, the geometric form of the specimens and the way they are prepared and exposed to the environment, and contact with different materials. Also, for coated specimens. the results will depend on the properties and uniformity of the coating [Martin, Saunders, Floyd & Wineburg].

Concrete -- Concrete technology is advancing rapidly, with advances coming from national high-performance concrete programs set up in several countries, and from private companies [de Larrard & Lacroix].. In the U.S., the National Science Foundation's Center for the Science and Technology of Advanced Cement-Based Materials (ACBM) is an example of such a national program, and the CONMAT Council's High-Performance Construction Materials and Systems Program plan [CERF] proposes a major national program for high-performance concrete which would include a number of activities intended to facilitate reliable service life predictions.

For prediction of service life of concrete, the previously-mentioned report, Durability Design of Concrete Structures [Sarja & Vesikari], is important in emphasizing the reliability approach and providing guidance on its application. At the same time, a more fundamental, material-science-based approach to prediction of performance of cement-based materials is being developed at the National Institute of Standards and Technology (NIST) [Bentz, Garboczi & Martys]. It is based on multi-scale computer simulation of phenomena taking place over time at the nanometer, micrometer, and centimeter scales, including microstructure development in the hardening cement paste matrix, simulation of transport phenomena in the pore structure at any age, and changes in properties of the bulk material at a scale that includes the coarse aggregate particles. The essence of their approach is outlined in Figure 1 (from [Bentz & Garboczi]), and a simulated microstructure of hardened cement paste from their work is shown in Figure 2 (from [Bentz, Garboczi & Martys]). Their models for simulating various mechanisms of degradation of concrete, as they are validated, provide a materials science basis for predicting service life to complement knowledge from other sources. A more immediate application of a model for predicting service life is that which Snyder and Clifton developed for predicting the service lives of the roofs of concrete vaults for storage of low-level nuclear wastes [Snyder & Clifton].

Organic Coatings -- While the principles remain the same, details of the prediction of service life of organic coatings are different from those for concrete. Coatings are a more diverse group of materials than concretes and they are more likely to be proprietary. Nevertheless, an important monograph on application of the probabilistic approach to prediction of service life of organic coatings has recently been published [Martin, Saunders, Floyd & Wineburg]. As with the contributions of Siemes and of Sarja and Vesikari to probabilistic service life predictions for concrete, Martin et al. emphasize the need for the reliability approach and provide guidance on how it can be applied. As always, critical steps are characterization of the environment and of the material, and determining how the environment affects the behavior of the material. Because of the relatively short life of most coating materials, the need for lengthy extrapolations from the results of relatively short-term experiments is less than for concrete, but there is still a critical need for appropriate and reliable data. For example,

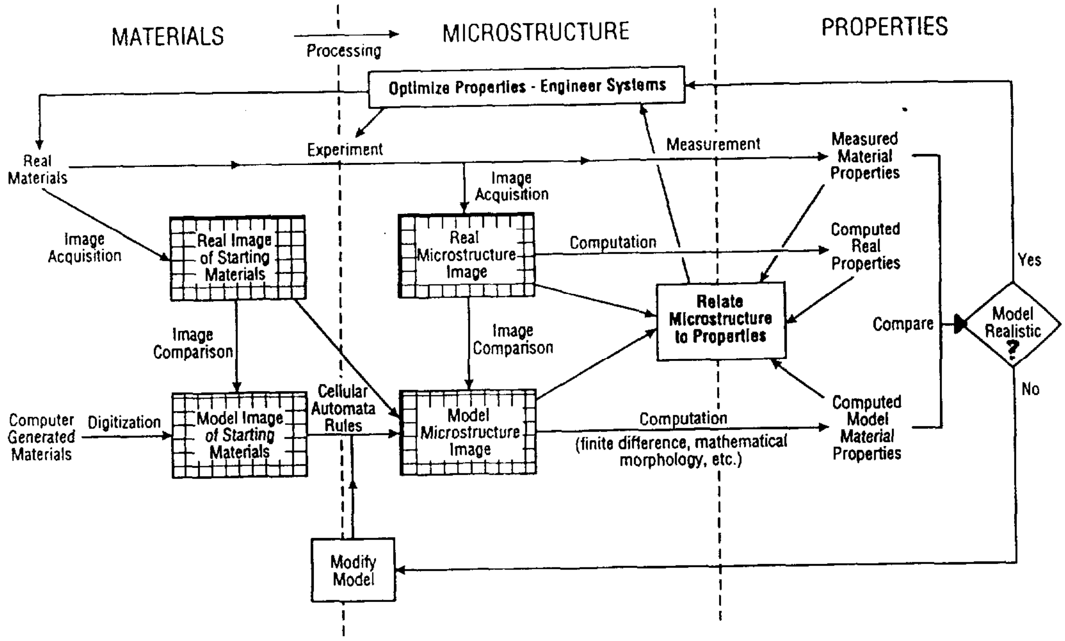

Fig. 1. Flow chart for modelling reactions of cement-based materials and simulating development of microstructure and properties [Bentz & Garboczi].

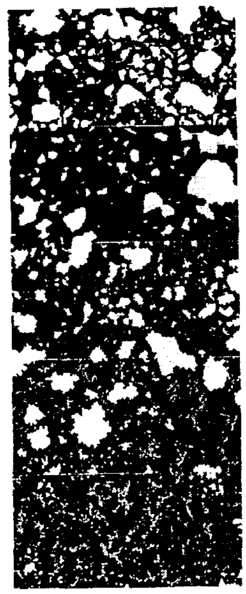

Fig. 2. Simulated microstructures of a hardened cement (tricalcium silicate) paste at, from left to right, increasing degrees of maturity. White areas, tricalcium silicate; light grey, calcium hydroxide; dark grey, calcium silicate hydrate, C-S-H; black, voids [Bentz, Garboczi & Martys.]

while it is well known that ultaviolet (UV) radiation is an important degradative environmental factor for most organic materials, the data needed by Martin and his coworkers are not yet available. To start to fill the national need for reliable spectral UV data to which attention has been drawn by the work of Martin et al., among others, NIST has begun a project to collect and compile spectral solar UV data into a standard reference database. When it is complete, it should serve all who need information about solar UV radiation, whether for studies of its effects on service lives of organic materials, or for studies of effects on biological systems important in medicine and agriculture.

Organization of Knowledge of Construction Materials Needed for Service Life Prediction

It has been mentioned several times that that prediction of service life is information-intensive. At present, the information needed to make reliable service life predictions, based on sound knowledge of degradation mechanisms and kinetics of degradative reactions in well-characterized service environments, is usually sparse or completely lacking, and there is little guidance for those who wish to make their own predictions. Without the reference data needed for service life predictions, those responsible for selection of construction materials tend to be conservative and rely on materials with known performance histories to reduce the risks of failure.

A step towards improved predictions would be development and standardization of documents providing more detailed guidance on how to apply a rational methodology for service life prediction, such as that outlined in ASTM E-632. This should probably be in the form of a series of related standards which would help designers address the service life prediction problem in essentially the same way and stimulate collection of comparable sets of data for entry into a common database. The technical basis for such standards is being documented by the joint CIB/RILEM Committee W80/140-PSL on Prediction of Service Life; (CIB is the Internatiional Commission on Building Research Studies and Documentation). A proposed 3-level hierarchy of standards for service life prediction is sketched in Figure 3 [from Frohnsdorff & Martin]. Another much-needed step would be development of comprehensive integrated knowledge systems for construction materials consisting of networked databases, knowledge-based expert systems, mathematical models for simulation and, possibly, other forms of computerized knowledge. In the author's view, the importance of linking databases, expert systems, and simulation models into a single computer-integrated knowledge system for the construction community [e.g., Frohnsdorff] cannot be overemphasized. It is consistent with "the metaphor of distributed intelligence" which Vice-President Gore so strongly supports [Gore]:

> We have in our hands and minds and souls the power to create this learning society, which harnesses the power of distributed intelligence and uses it to improve our lives.

To suggest the nature of the opportunity, sketches representing our construction materials knowledge system as it appears now (Figure 4) and as it might be early in the 21st century (Figure 5) if the various computer representations of knowledge of construction materials were brought together in a computer-integrated knowledge system network accessible through the Internet are shown [from Frohnsdorff, Clifton, Garboczi & Bentz]. A workshop to discuss development of such a system, sponsored by the CONMAT Council, ASTM and NIST, was held in June 1996 [CONMAT]. Representatives of many construction material groups including aluminum, asphalt, coatings, composites, concrete, masonry, plastics, roofing materials, smart materials, stainless steel, steel, and wood, participated. All the groups represented undertook to start the task of computerization of knowledge for their industries with a view to becoming part of the proposed computer-integrated knowledge system network. While the ways in which this will be done may differ among the industries, all appreciated the benefits of computerizing materials knowledge of many kinds, from product lists to technical data, and all saw a benefit in having some coordination among the groups. As it develops, the network will aid rational, science-based service life predictions for materials for the next generation of constructed facilities.

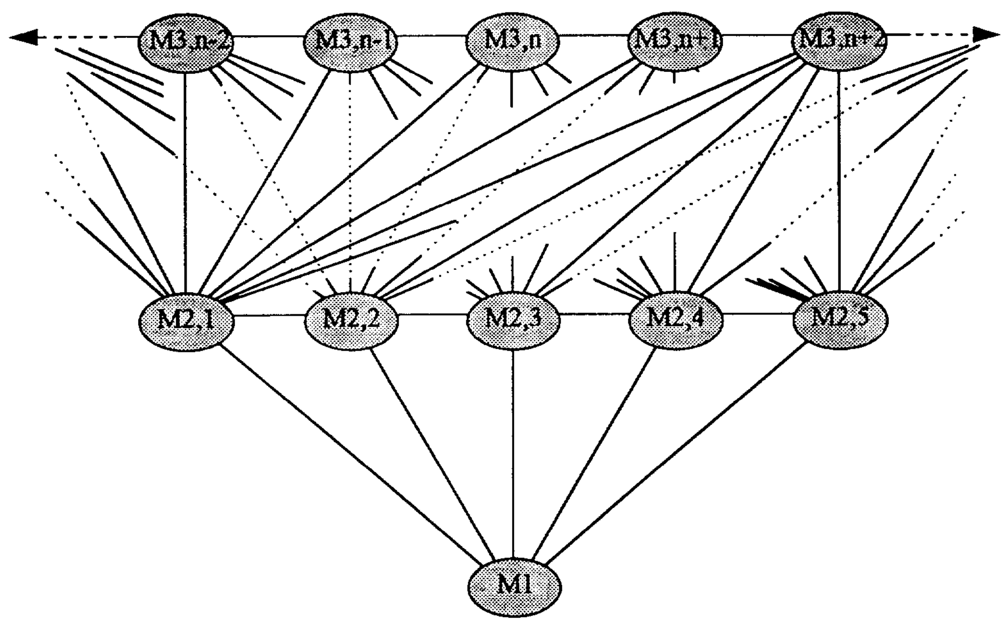

Fig. 3. A 3-level hierarchy of standards proposed to aid service life predictions for construction materials.

Summary And Conclusions

Predictions of the service lives of new materials of construction, or of any material of construction under especially demanding conditions, are essential. However, present predictions are often unreliable. Among major factors contributing to uncertainties in service life predictions are lack of knowledge about: service conditions, degradation mechanisms of materials, kinetics of degradation of materials under well-defined service conditions, and the appropriate failure criteria. Equally important in the present state of knowledge are variations in the qualifications (knowledge and insights) of the persons responsible for making the predictions. To improve the situation for the next generation of constructed facilities, it is recommended that some ongoing activities be expedited and some new actions be taken. Specifically:

1. Guidance on use of a standard approach to prediction of service life, such as that presented in the RILEM Technical Recommendation, Systematic Methodology for Service Life Prediction of Building Materials and Components, should be provided to the construction community. The guidance could come from subsidiary standards which are being developed in ISO TC59/SC3/WG9, Design Life of Buildings, to aid application of parts of the methodology (for example, characterization of service environments).
2. Guidelines expressing recommended qualifications for those entrusted with the responsibility of predicting service lives of construction materials and components should be drafted.
3. Comprehensive computer-integrated knowledge systems (CIKS) for construction materials, in standard formats, should be developed and made accessible through the Internet. The CIKS, which would have general value to the construction community, should include data, simulation models and knowledge-based expert systems needed to support service life predictions.

Some of these developments are already taking place in committees of ASTM, CIB, RILEM and ISO, but much more must be done if we are to make possible the selection of the optimal materials for "a new generation of safe and durable constructed facilities."

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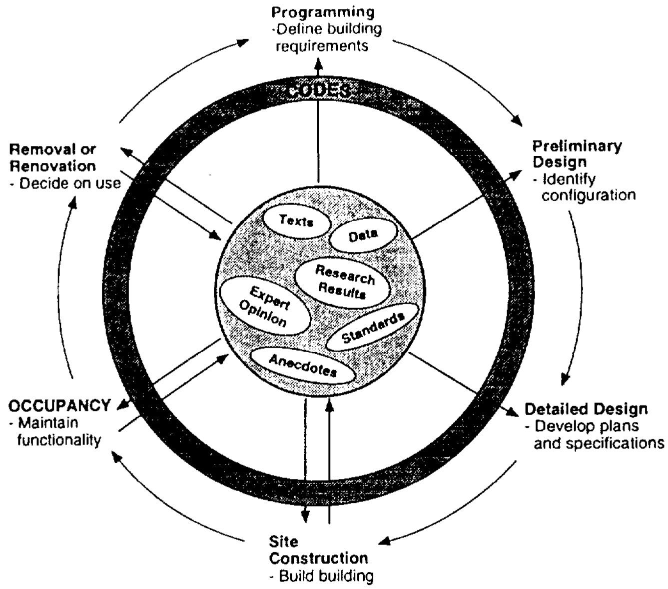

Fig. 4. The construction cycle and the fragmented knowledge system for construction materials as it might be represented at the end of the 20th century

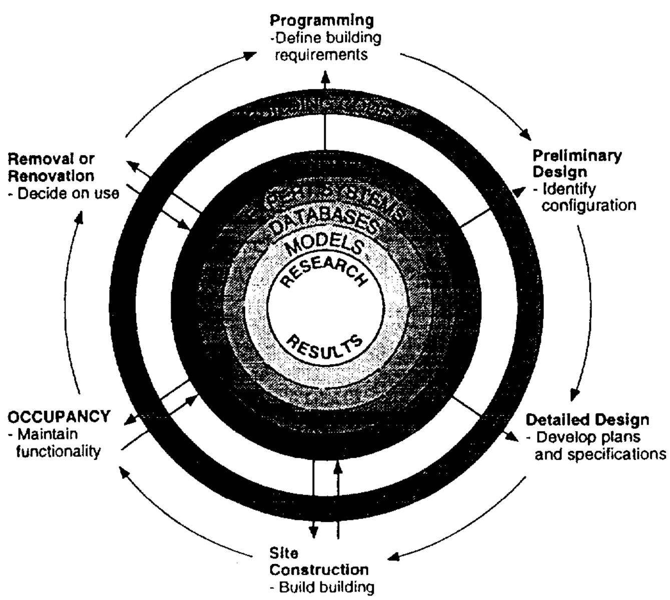

Fig. 5. The construction cycle and the integrated knowledge system for construction materials as it should be early in the 21st century.

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